Special Relativity is not Based on Causality.

Abstract

The standard view that the foundations of Special Relativity lie in causality is challenged. It is argued that the literature on tachyons strongly suggests that causality is in no way basic to Special Relativity; that the standard view distorts the role of the Invariance Principle; that no satisfactory understanding of the idea of causality is available; that the real foundations of Special Relativity lie in the concept of invariance. It is suggested that a philosophical motive behind the standard view is to keep the idea of the physical tied to that of the material.

1. INTRODUCTION

Almost everyone who has a considered opinion about what the conceptual foundations of SR (Special Relativity) might be, thinks that they lie in causality.[1] Cause is said to be the basic concept of the theory. The basic thesis (statement, postulate) of SR which makes use of this concept is said to be the Limit Principle: nothing (including causal processes) goes faster than light. This opinion about SR's foundations which I will call the standard view, is a philosophical one, not just because it is about conceptual foundations but also because many who hold it envisage the success of a programme attributed to Leibniz. It reduces the metaphysically uncomfortable ideas of space and time to the single familiar idea of physical material cause. This picture of the theory as specifying for itself how its bold new structure rests neatly on secure old foundations, as basic as can be, does much to shape our wider ideas about how people build their concepts and theories and about how these grow out of older concepts and theories.

Despite the widespread enthusiasm for it, and the careful and ingenious way it has been developed, the standard view remains doubtful. The Limit Principle is very probably not even a consequence of SR and certainly not among its basic postulates. It is uncertain which concept causality is and whether the relation is fundamental to any thing. I think that the standard view is false and that is what I will try to argue.

One sign that the standard view is dubious can be seen in the extensive literature on tachyons (a literature now in existence for twenty years) which has failed to show that SR forbids them. The idea of a tachyon is the idea of a particle which goes faster than light. The hypothesis that there are tachyons is flatly inconsistent with the Limit Principle. Thus, if the Limit Principle is a basic postulate of SR there must be a brief, decisive refutation of the tachyon hypothesis simply by invoking that postulate. The literature on tachyons presents a very different picture to us. A rather strange, but consistent dynamics has been worked out for tachyons within the context of SR: mass, momentum and energy can be defined for them. Their oddities include that mass for tachyons is an imaginary quantity and that the temporal order of events in their histories varies under Lorentz transformations. Now, it is probable that there are no tachyons. It may even be the case that they can be shown physically impossible - because their quantum fields make no sense, say. But if the existence of tachyons is consistent with SR then the theory gives no particular significance to causality. Lastly, unless tachyons can be ruled directly out by the Limit Principle used as a postulate, then neither that Principle nor the causal relation has a fundamental significance in SR.[1]

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[1] But see Lacey (1968) Smart (1969) and Earman (1972) for opposite opinions.

The crucial target which any relation proposed as basic to SR must hit is this: the relation must allow us to identify the light cone structure of Spacetime. It is, of course, extremely obvious that the light cone is basic to spacetime structure and to SR. If the Limit Principle is a consequence of SR, then causality is co-extensive with the surface and interior lobes of the light cone.[2] If the Limit Principle is either false, or not a consequence of SR, or not a postulate of SR then, respectively, causality is not co-extensive with the light cone, not specified by SR as co-extensive, or not postulated in SR as the foundation of the light cone. In any of these cases the standard view would be mistaken.

Whether or not the Limit Principle has any status in SR it is certainly false that causality is the only relation which identifies the lightcone or is said to do so, quite fundamentally, by SR. Clearly, but trivially, light (electromagnetism) itself does so. The relation "x is connectible with y by a (possibly reflected) light path" identifies the surface and interior of the cone. Rather more interestingly, the relation 'occurs at another time than' (where this is understood to be determined without reference to any coordinate system or reference frame) - the elsewhen relation - does so. This is an agreeably direct and simple consequence of the theory in its earliest and most naive forms. There is, then, no obvious reason to think that SR will fall unless we use causality to identify the light cone. All that will collapse is the reductive, philosophical programme of defining spacetime relations by means of causal ones.

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[2] More strictly, the relation expressed by 'x is causally connectible with y' is coextensive with the relation expressed by 'x is on the surface or in the interior lobe of the light cone at y' iff the Limit Principle is true. The Limit Principle identifies light as the limit of causality.

[1] What is intended by appeal to the status of being a postulate, being basic or being fundamental is looked at more closely in § 4 pp. 20-21.

The Invariance Principle (that is, that the laws of physics, and of light propagation in particular, are invariant under transformations of the Lorentz group) is a far more prominent thesis of SR than the Limit Principle is. However, it is widely regarded in philosophical literature as laden with non-factual, merely conventional elements, and it is held that the Limit Principle exhausts its factual core. Both these views are false, I will argue. The Invariance Principle is not convention laden and the Limit Principle forms no part of what it asserts.[1] Einstein seems to have been responsible for this widely held opinion. Something which is at least very like it appears in his 1905 paper. His discussion of simultaneity does seem to be based on the Limit Principle. His task here was to make the conceptual point that the apparently synthetic necessary truth that simultaneity is absolute could be undermined. He sees the Limit Principle as requiring that simultaneity in a frame be settled by a definition, a convention. What he goes on to say in embracing the Invariance Principle, however, is not that the finite speed of light is the limiting speed for every real process, but, in effect, that it is the invariant speed for all Lorentz frames. Evidently, he thought that the one thing entailed the other. It is not at all clear how it might do so. In the coordinate-free treatment of the metric structure of spacetime the crucial statement about the light cone is that it is null. Once again, this has no obvious consequence in relation to the Limit Principle. It is perhaps worth noting that the "paradox" by which Einstein says he was led to SR actually suggests the idea of the invariance of the speed of light just as readily as it suggests it to be a limiting velocity. The "paradox" runs thus: if one could equal the speed of a light wave, it would appear to one as a standing wave and no such thing is known. This suggests that the attempt to approach the standing electromagnetic wave by approaching the speed of light must also fail, so that light will appear the same for all attempts to approach it.

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[1] By no means all who might describe themselves as causal theorists subscribe to this view. See Malament (1977), for example.

The consistency of the tachyon hypothesis with SR is of real importance for my argument in showing that the Limit Principle is not a consequence, certainly not a basic postulate, of SR. But it is not all important. I argue, also, that causality is too indefinite a concept to play the part which the standard view envisages for it. Attempts to explicate it run into various problems (especially the problem of circularity) if one wants to use it to reduce the ideas of space and time to causality. Again, to commit SR to causality as a basic concept is to make a problem of its consistency with quantum theory (though I shall not argue that at length). Lastly, I argue that we can define the light cone in ways quite independent, conceptually, of causality and even by a means of a relation which is not even co-extensive with causality, whether the Limit Principle is true or false (or entailed by SR).

This makes my argument look as if it conflicts directly with what is probably the most interesting and penetrating work done in recent years on the conceptual structure of SR. Zeeman (1964), Malament (1977) Winnie (1977) and others claim to define various structures in spacetime on a causal basis. For example, the Lorentz group (Zeeman), orthogonality (hence simultaneity) (Malament) and even the complete metric congruence structure of spacetime (Winnie) have been defined on the slender basis of causal topology. This work looks back to the early, but previously neglected, work of Robb (1914). The appearance of conflict is somewhat illusory, however. All these constructions can indeed be made on a topological basis, just as these writers say they can. But the basic relation of this topological structure is not (said by SR to be) causality. It has to be some other relation, either the elsewhen relation or the light-connectible relation itself, for example. But though I dissent from this fruitful body of theory on only a single issue, it is the fundamental issue.

In section 2 I look at the role played by the Invariance Principle in certain standard formulations of SR, arguing that it carries much of the factual import of SR and that its supposed taint of convention is illusory and based on certain confusions. In section 3 I glance at some simple, qualitative findings about tachyons and relate them to the Invariance Principle. Section 4 discusses various accounts of the causal relation arguing that some standard accounts would be unsuitable for their envisaged purpose even were the Limit Principle a consequence of SR. Lastly, in section 5, I consider whether the surface and interior of the light cone has any deeper significance for spacetime structure than the surface and exterior has. I conclude that it has not, which finally demonstrates that causality can have no unique significance for SR, whatever the status of the Limit Principle might be.

2. THE INVARIANCE PRINCIPLE

A rather satisfactory picture of the import of SR is given by the claim that the Invariance Principle is a central factual postulate of it and that this Principle does not entail the Limit Principle. An advantage of this picture is that it is cast in rather familiar ideas which make it clear how and where it conflicts with the standard view. Since that part of the physics of tachyons which is of most interest for the matter in hand is drawn out of the Invariance Principle, and this physics shows that the principle is independent of the Limit Principle, it will be useful to look with some care at what Invariance is. But though this way of viewing SR is rather satisfactory I will say, at the end of the section, why I do not believe that it offers us a suitably basic picture of the factual structure of SR.

What is the Invariance Principle, more explicitly? How clear is it that it is not a partly conventional, non-factual, statement? To answer either question we must begin by distinguishing two styles of interpretation of SR and see that the Invariance Principle plays somewhat different conceptual roles in each. By and large, it does no harm to run the two styles of interpretation together but this is so only if one does not think that the Invariance Principle is some sort of convention. What are these two styles of interpretation?

I call the first the spacetime interpretation. It has an ontology of events (alternatively of 4-dimensional objects) and speaks of a spacetime (but not of a space nor a time). Spacetime in SR has zero curvature and Minkowski metric in which physical quantities appear as 4-vectors or 4-tensors. A very wide range of coordinate systems may be used in the description of spacetime and its physics, but assigning the same time coordinate (or the same space coordinates) to different events is not interpreted as reflecting, even relatively, the concepts of simultaneity (or rest) since these are no part of the scheme of concepts of this interpretation. Further, the use of co-ordinate systems is not essential to spacetime physics, co-ordinate-free treatments of it being quite standard. Light is distinguished neither as invariant in speed nor as the fastest signal, since ideas like 'speed' and 'fastest' do not belong in this interpretation. Light is picked out in that light trajectories always lie in cones of null geodesics, one of which is defined at each spacetime point.

The second style I call the relativity interpretation. It has a familiar, classical ontology of continuant spatial objects persisting in time. It uses the idea of a frame of reference, a relative space and a relative time. The frame defines (relatively) the same place at different times and thus the concepts of rest, motion, speed and velocity. It also defines (relatively) the same time (simultaneity) at different places. Light is marked out as having an invariant speed for every frame of the interpretation. Whereas one can do spacetime physics without coordinates, it is meaningless to speak of a frame-free relativity physics. The concepts of the relativity interpretation make sense, in SR, only with respect to some frame. For these, and other, reasons the idea of a frame of reference does not correspond in a simple way to the idea of a coordinate system. Consequently the part played by the Invariance Principle is a little different in each interpretation. What are these differences?

It is widely agreed that the spacetime interpretation of SR is the more fundamental one. Two principles about coordinate systems for spacetime make sense in this interpretation. The Principle of General Covariance says that any coordinate system for spacetime is admissible so long as it is continuous and distinguishes timelike from spacelike coordinate trajectories. So it admits skew (time-skew) and curvilinear coordinates as well as the familiar Lorentz linear, time-orthogonal coordinates. The Principle says that the laws of physics are covariant (form invariant) under the very general group of coordinate transformations which map from any one of these systems to any other. This really amounts to treating spacetime and the vectors and tensors in it as geometric objects which are what they are irrespective of the coordinates - mere devices of book-keeping - which are used to describe them. The form of any law which is invariant under this general group of transformations is not very simple. It contains terms which are functions of the affine connection and metric tensor of spacetime. The Invariance Principle is a more special statement about a particular set of coordinates within the general set and about the particular group of coordinate transformations which connect them. The particular set is, of course, the linear, time-orthogonal (Lorentz) coordinates and the particular group is the Lorentz group of transformations. What the Invariance Principle says is that the forms of laws invariant under transformations of the Lorentz group is really very simple, for it need contain no terms referring to the affine connection or metric tensor. That constrains the laws of physics in a rather significant way. In flat spacetime, at least, General Covariance places no additional constraints of a physical kind on the laws. (See Weinberg (1972) pp. 92-3 for a clear discussion of this). Obviously, the fact that the set of Lorentz coordinates and its group of transformations are included in the more general set of coordinates and its group of transformations does nothing to weaken the constraints imposed by the Invariance Principle on the laws of physics. Thus it seems apt to focus on this principle as elegantly conveying a main factual assumption of SR. Of course it figures very prominently in the structure of SR.

Clearly, in the spacetime interpretation, the Invariance Principle does nothing to restrict the range of admissible coordinates. It does not forbid the use of skew or curvilinear coordinates. There is no sort of conflict between it and the Principle of General Covariance.

In the relativity interpretation, by contrast, the Invariance Principle does function as restricting the choice of reference frames. It says that only Lorentz (or inertial[1]) frames may be used. Where does the Principle of General Covariance fit into this interpretation, then? The relativity interpretation does not let us formulate a principle which might be properly seen as a counterpart of General Covariance. Partly, this is because the idea of a reference frame is really quite different from that of a coordinate system. Frames differ just when they define different spaces (sets of rest points) or times (set of simultaneous events). So the ideas of a space, a time, of rest and simultaneity go inextricably together with that of a frame. However, a mere shift of origin, or a purely spatial rotation of space coordinates results in a new coordinate system. So frames correspond, at best, to classes of coordinate systems. However, beyond all this, the ontology connected with the idea of frames is different from spacetime ontology. This means, for present purposes, that whereas terms involving the affine connection have a purely geometric sense in unified spacetime (which is what permits General Covariance) the split into a space and a time needed for frame of reference ideas prevents these terms from carrying over a merely geometric meaning. Though one gets the same laws formally in an accelerated frame as one gets in the corresponding curvilinear coordinates, by involving the metric tensor and the affine connection, one has to fabricate inertial forces and introduce dynamical concepts, to deal with these terms. These make no more physical sense in SR than they did when classical physics considered the consequences of using accelerated frames. For these reasons, the Principle of General Covariance is conceptually prevented from having any proper counterpart in the relativity interpretation. So we are obliged in that interpretation to read the Invariance Principle as restricting the class of admissible frames.

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[1] One has to be a little cautious here. A Lorentz frame is, in fact, something more determinate than an inertial frame, for the latter specifies something only about rest points of a frame. See pp. 11-12 below.

In this way, the two interpretations give somewhat different pictures of where Special theory ends and General theory begins. The relativity interpretation makes it look as if General Relativity starts with the extension to "accelerated" frames. But it is not really here that the important generalization comes. As the spacetime interpretation shows, it is in the extension to curved spacetime with the entry of gravitation that General Relativity begins.

These observations on the Invariance Principle would not be of much importance were it not widely held that this Principle is really a convention, with the Limit Principle as its factual core. The view that Lorentz simultaneity is a convention within a frame of reference is often tied closely to the idea that the Limit Principle is basic to SR and that causality is its fundamental concept. In the light of that view, it seems to some that the tachyon hypothesis must completely subvert the relativity of simultaneity, since if the Limit Principle did not obstruct attempts to set up absolute simultaneity, nothing else could do so. But this overlooks the role played by the Invariance Principle in tachyon physics. Of course, one can hardly see what this role is if he thinks the Invariance Principle has nothing factual to say. So we need at least a brief look at the doctrine that simultaneity (as prescribed by the Invariance Principle) is a convention.

Conventionalism about simultaneity has always been expressed within the relativity interpretation and makes no sense outside it. The convention imposed is said either to stipulate a *speed* for light within the chosen frame or to stipulate classes of *simultaneous* events within the frame. These are not concepts of the spacetime interpretation. It is important to realise that the convention is supposed to be adopted within a frame; that is, after one has chosen the frame. Thus the relativity of simultaneity is regularly distinguished from its conventionality. There is no counterpart of this in the spacetime interpretation. One chooses a system of coordinates.

That fixes all the assignments of coordinates to events, which can intelligibly be made. There is no place for a further convention to govern some analogue of simultaneity, not because coordinate systems do not traffic in such a concept, but because nothing is left open, once the system is chosen, which could be fixed by a further convention about coordinates. Not only is there no need, there is no room within a coordinate system for conventional non-factual stipulations to determine anything analogous to a speed for light or simultaneity. The system already assigns all coordinates which can be assigned. The trouble lies in a faulty match between the idea of a coordinate system and one idea (common among philosophers) of a frame of reference.

In the light of this, conventionalism might take one oftwo forms, neither of which looks defensible. One form of it is like the familiar conventionalist view of the metric of continuous physical space. The facts about space are said to be exhausted in its topological (perhaps its differential) structure as continuous (perhaps smooth). The language of metric geometry is a non-factual, purely conventional determination of language imposed upon this factual core. Similarly, by means of a conventional determination of simultaneity in every frame, the Invariance Principle is seen as a non-factual, purely conventional imposition of language upon the factual core of the Limit Principle. It is this version of conventionalism which seems to be most commonly urged about simultaneity.

But this idea is fatally open to the objection that there is no counterpart to this convention in the spacetime interpretation.[1] If SR contains non-factual, merely conventional sentences in the one interpretation, then it must surely contain them in the other on pain of a radical mismatch of factual content in the two interpretations. But there is no counterpart convention in the spacetime interpretation, as we just saw. Assigning the same or different time coordinates to any pair of events is done in selecting the coordinate system, not by a further convention after the system is chosen. The trouble lies in a confused, inadequate idea of reference frame inherited from classical physics, an idea with which philosophers have wanted to persist. One determines a frame by fixing on a *set of rest points*. In classical physics, where simultaneity is absolute, the idea is perfectly adequate. But this philosopher's picture of a reference frame is clearly *not* adequate for SR and is not the idea of a reference frame used in physics text books which is the idea of a fully Lorentz-specific frame. The philosopher's reference frame corresponds to the idea of a "coordinate system" which specifies the only x-, y- and z-constant trajectories in spacetime, but no t-constant trajectories. It is a 'system' with one coordinate missing. In fact, it is not a coordinate system at all. The result of persisting with the use of such an object is that one cannot translate down into the relativity interpretation all the coordinate-relative facts which are stateable in the spacetime interpretation. What the conventionalist sees as a set of factually empty sentences imposed by a dispensible convention is really the residue of (relative) facts which one is not able to state in the relativity interpretation unless an adequate frame of reference is used. ?

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[1] We must distinguish conventions which fix the formal structure of a theory - which true sentences are postulates, which definitions and so on - from those which are said to incorporate sentences into the theory which have no corresponding facts or which are not factual. The latter sort of conventions are in question here, not the former. The distinction is discussed in more detail in Nerlich (1976) pp. 126-7.

But someone might hold a quite different theory about how simultaneity is governed by a convention even though an adequate idea of reference frame is used. He might claim that, though there are frames of reference fully corresponding to all the significant classes of coordinate systems allowed by General Covariance, it is by a convention that we choose only Lorentz frames. Though we *might* choose frames corresponding to linear but time-skew coordinates, for example, our convention leads us to avoid them. The crucial difference between this conventionalism and the former is that all the frame-relative attributes and quantities which correspond to coordinate components are seen as relative facts, not factually empty conventions. Thus, within a frame, the distinction between simultaneity and non-simultaneity is just as much a matter of (relative) fact as the distinction between rest and motion is.

The advantages of this style of conventionalism are that it uses a satisfactory idea of reference frame and that it seems to have some support from the Principle of General Covariance. The view might be that the Principle licenses a very general set of frames. We choose among them, by a factually arbitrary convention recommended only by its simplicity, just the Lorentz frames.[1] The trouble is that there is no inference from the admissibility of coordinates under the Principle to the admissibility of the corresponding frames. To curvilinear (time-like) coordinates correspond accelerated frames and these are plainly not admissible, on dynamical grounds, for the purposes of the relativity interpretation. The position as regards linear but time-skew coordinates is not so clear and, I think, has never been adequately focused on in the philosophical literature. (But see Friedman (1977)). Skew frames (if I may call them that) have anisotropic spaces so far as light propagation (and a number of less obvious factors) is concerned. This is well known. But the anistropy is seen as something non-factual, conventional in the first sense, rather than as the (relative) factual matter which it really is. (See

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[1] Quite obviously there is a conventionalism about coordinate systems, which says that we select, by convention, only Lorentz systems from the very general set because of their simplicity. This appears as a (philosophically) rather trivial observation on the relation between the Invariance Principle and the Principle of General Covariance. It has nothing to do with such concepts as simultaneity and one-way velocity. It is doubtful to what extent there actually is such a convention since a wide range of coordinates, or sometimes no coordinates at all, are in moderately frequent use.

Grünbaum (1973) pp. 355). I have argued elsewhere that the anisotropy makes such frames inadmissible. Thus simultaneity and the Invariance Principle are conventional in neither of these ways. (The argument of the last five paragraphs condenses part of Nerlich (1981)).

To sum up this section so far: the Invariance Principle is a main factual assertion of SR, best understood in the spacetime interpretation as placing stringent constraints on the form of physical laws under a central group of coordinate transformations. The Principle is innocent of conventional taint (in the sense of containing non-factual elements). The theory that it requires a convention of simultaneity springs from confusions about the relation between coordinate systems in the spacetime interpretation and frames of reference in the relativity interpretation. This explains and defends the positive view of the foundations of SR which I stated in the first sentence of the first paragraph of the section.

Nevertheless, there are reasons for thinking that the Invariance Principle is not quite the right replacement for the Limit Principle. First, the Invariance Principle tells us something crucial about certain coordinate formulations of physics for spacetime. But facts about its coordinate systems can hardly be what is basic to spacetime and, indeed, one can do spacetime physics without the use of coordinates at all. Second, it would be nice not to have to concern oneself with the rather inelegant relationship between General Covariance and Lorentz Invariance, even if the first point were waived. We can avoid the relativity to coordinate systems or reference frames (together with some of the problems just discussed, though some illumination is gained by discussing them, I hope) by citing the metric facts about spacetime; that light geodesics are null, spacelike intervals (s^2) negative and time-like ones positive (for appropriate signature) and, generally, by describing the metric tensor of spacetime. It is, in fact, the metric structure of spacetime which bestows on the Lorentz coordinates (and their connecting group) the special symmetries which make possible the simple forms of physical law. It makes the times and spaces of the frames of reference corresponding to these coordinates simple and isotropic. Last, the Invariance Principle is framed in the concepts of the spacetime *metric*. Now the Robbian constructions of Zeeman, Malament, Winnie etc. mentioned in § 1 strongly suggest that metric concepts are not basic to SR. (But see Sklar (1977).) One only needs the topological structure of the conical ordering of spacetime. Then one can *derive* the whole metric congruence structure.

I propose, instead, that a fundamental relation of SR is the *elsewhen* or non-simultaneity relation ('x occurs at a time other than y'). The basic assertion which uses the relation is that x occurs at a time other than y iff x ≠ y and x is in, or on the surface of, the light cone at y. This is suitably topological. There is no other relation which, *according to SR theory*, allows us to identify this relation and thus reduce it (save for light connectibility itself). I will argue later, however, that SR can be based in a different way on a quite distinct relation, with equal satisfactoriness.

In the next two sections I will frame the discussion in terms of the Invariance Principle, since I think this is more familiar and easy to follow.

3. TACHYONS

This section considers the physics of tachyons rather briefly and roughly. In the course of it, I argue for these conclusions: it would be reasonable to expect that tachyons, if there were any, would be useless for signalling or synchronising clocks; nevertheless it is not inconsistent with the Invariance Principle that they should have such a use; their use in synchronising clocks could not override the relativity of simultaneity; these facts about signalling do not disqualify tachyons as causal particles; at least one attempt to disqualify tachyons as causal particles appears also to attempt to deduce the Limit Principle from the Invariance Principle, contrary to causal theorists' views that the former principle is, relatively, the more basic.

A tachyon is a particle which goes faster than light. If a particle ever does so, then it always does so. A glance at the relativistic formula for kinetic energy makes it clear that the energy of a particle increases without limit as its velocity $\underline{v}$ approaches $\underline{c}$ (from $\underline{v} < \underline{c}$). One could never accelerate a slower than light particle to superluminal speeds. If $\underline{v} > \underline{c}$, then both the energy and momentum become imaginary quantities, if the mass remains real. But if an imaginary (complex) quantity is admitted as the mass of a superluminal particle then the energy and momentum remain real though they increase without limit as $\underline{v}$ approaches $\underline{c}$ (from $\underline{v} > \underline{c}$). Thus a tachyon is always superluminal just as ordinary particles are always subluminal. This entails that there can be no procedure of measuring the mass of the tachyon at rest and we may suppose it to be imaginary. Thus the velocity and energy-momentum 4-vectors of these particles are always spacelike at each point.

The Invariance Principle tells us not only which properties of tachyons are frame invariant but also which ones are not. This negative aspect of the message is more important for the argument of this section.

For example, the velocity and the energy-momentum 4-vectors for tachyons are spacelike at every point of a tachyon world line. It would seem, therefore, that the energy (that is, the time component of the latter vector) will be negative in some frames, though positive in others; further the velocity vector may have a negative time component, which appears to mean that "it travels backwards in time". However, if we reflect more carefully on what the Invariance Principle implies, we see that it requires that events in the history of a tachyon do *not* have an invariant time order: that relative to some frame A, the tachyon is *emitted* at E_1 and travels to the point of its (frame relative) later *absorption* at E_2, whereas relative to another frame B it is *emitted* at E_2 and travels to the point of its (frame relative) later *absorption* at E_1. In the light of this reinterpretation of the (relative) temporal ordering we may reinterpret the energy of the particle as positive in each frame also. But, then, the tachyon is described in frame A as an antiparticle of that described in frame B. This device is called in the literature the Reinterpretation Principle. It shows how the Invariance Principle constrains the physics of tachyons so that they become consistent with SR.

The laws of tachyon physics must be Lorentz invariant if they are to be compatible with SR (and only the possibility of a physics consistent with SR concerns us at the moment). Thus no law or laws of tachyon physics can specify conditions sufficient for the emission of a tachyon by a subluminal particle since, if such an event occurs in any frame, there will be infinitely many others in which the same conditions suffice for the *absorption* of a tachyon. So, first, there can be sufficient conditions only for the emission-or-absorption of tachyons by subluminal particles. It is best to speak, in spacetime language, of laws specifying conditions for the existence of a tachyon *pencil* (of one or more rays) *at* a certain spacetime point on a subluminal particle, this being neutral as to which are emitted and which absorbed. Secondly, though this does allow for the interaction of super-with sub-luminal matter (without which the hypothesis of tachyons seems empty), it strongly suggests that the conditions sufficient at t_1 for a tachyon pencil at $t_{1+\epsilon}$ on particle a cannot be exhausted in conditions local to a. How can I tinker with a at t_1 to make it absorb a tachyon at $t_{1+\epsilon}$ unless there already is a tachyon elsewhere at t_1 free to be absorbed?

This last point is not at all straightforward. Consider the case of the light cone. Nothing in SR entails that light is characteristically emitted in expanding spherical waves rather than characteristically absorbed in contracting ones. Nevertheless, that is invariably the case. This asymmetry between absorption and emission (the preference for retarded over advanced solutions of wave equations) seems to be related, at a deep level, to the directedness of time. It has no explanation in terms of known fundamental laws, all of which are time-symmetric and I think it fair to say that it is still not well understood. Popper's attempt to explain it by appeal to improbability is circular. He argues that the contracting wave front culminating in the event of absorption requires an immense, non local conspiracy of conditions at each point (at some time) on a sphere with the absorption point as centre. This conspiracy directs radiation inwards to this central point. But why is this a conspiracy of events of an immensely improbable kind, whereas the time-reflected existence of a spherical radiated wave front moving outwards from a point of emission is not? Simply because we always get the retarded solution, never the advanced one. If we did always get the advanced solution, as the laws allow perfectly well, we would not regard it as at all coincidental.[1] We might now argue for the conspiracy of events by appeal to what is, essentially, our sense of the direction of time. This appeal would be somewhat inarticulate, since it is unclear whether this raises anything independent of what we want to explain or whether the appeal refers to anything well understood. The analogy with the tachyon example is imperfect, but it suggests that assuming localised control of tachyon interactions, which is something essential to signalling, surely, is not at all straight forward and needs to be considered very cautiously.

If there can be no law-like invariant distinction between the emission and the absorption of tachyons, then it would seem that they cannot be used in any direct way to send signals or transmit information. This conforms to what one might expect. But it is not, I think, a direct entailment of the Invariance Principle. The ideas of a signal (a mark, information) and the sending of it are, for physics anyway, ideas of irreversible processes. They belong in thermodynamics. One might expect that the "laws" of thermodynamics, like the more fundamental time-symmetric laws of SR proper, will be invariant under Lorentz transformations. If that is so, then irreversible processes will be irreversible in the further sense that their temporal order will be invariant under the Invariance Principle. In this "natural" sense, then, it will be the Invariance Principle (not the Limit Principle) which confines signalling and information transfer to the light cone. For this reason, too, the causal paradoxes sometimes associated with tachyons (e.g. Salmon (1975) p. 122-3) will not arise, since they presuppose that one can use a tachyon to signal. (See Feinberg (1967) Appendices A and B pp. 1101-1103 for a more detailed account of the emission - absorption and signalling problems). Again, for the same reason, tachyons can have no simple use as devices for synchronising clocks.

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[1] A similar objection holds if we understand Popper's appeal as directed towards the simplicity of the point of emission as a proper locus of explanation. If we always got the advanced solution then we would come to regard the subsequent absorption of the spherical wave front at a point as explaining, in a simple way, why there was a collapsing spherical wave front preceding it.

Of course, the relevant "laws" of thermodynamics might not be constrained by the Invariance Principle, being statistical, possibly local in spacetime and in the nature of boundary conditions rather than true laws. If so, things are not so simple. There might be, for each spacetime point, a sort of thermodynamic (spacelike) tidemark in spacetime so that tachyons could be marked only if their velocity vectors point towards the forward (dry) region of spacetime beyond the tidemark at that point and marks erased from them only if their velocity vectors point towards the backward (wet) region of spacetime.[1] Then, it might seem, tachyons could be used to set up a *de facto*, statistical sort of simultaneity, but an absolute one nevertheless.

But this would leave SR and all its conceptual structure quite untouched. It would still be true that the fundamental laws of physics were Lorentz invariant. It would still be true that everything observed in every Lorentz frame (that is, *using standard light signal synchrony*) would be physically possible and, for much the most part, perfectly as usual. The statistical, *de facto* tachyon simultaneity would, perhaps, mark out some frame uniquely as the one in which this simultaneity coincided with standard signal synchrony. But nothing connected with true physical laws and their invariance would oblige us to prefer this frame and it would, probably, not even be strongly recommended by convenience (unless we could, somehow, *see* by means of tachyons). Statistically irreversible processes would be irreversible in only a weak sense, since their reversals would be observed in an infinite class of frames of reference which our fundamental theory of space and time assures us are admissible.

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[1] The tidemark metaphor is not intended to suggest that a tide *moves* in spacetime.

Consider another possibility. Suppose we could deduce in SR with tachyon-theory that a tachyon event occurs at a subluminal particle iff the tachyon velocity vector is orthogonal to the velocity vector of the particle prior to the interaction. Given the natural absorption-emission variance picture of tachyons this would have an apt sort of indeterminacy of temporal direction. Thus in the rest frame of any particle(s) which subsequently emits-absorbs a tachyon, the tachyon trajectory would define the class of events which are simultaneous (Lorentz simultaneous) by means of a direct physical criterion-tachyon connection. Given that tachyons are not signals, we would have to gather information as to which events were thus tachyon connected, presumably by ordinary, subluminal means, only well after the events (if at all). The point is not how soon one could find out what this physical criterion applies to, but whether, in fact, there would be one. However, it is quite obvious that this physical criterion does not fix simultaneity in any *absolute* way. It would simply give us back the standard Lorentzian relative simultaneities, with distinct simultaneity classes for distinct frames. The point of this example is to demonstrate that the relativity of simultaneity does not depend on the absence of particles propagated outside the light cone, *even if these somehow provided criteria of simultaneity*.

If tachyons are to be cast in the role of causal particles so that tachyon connections are causal connections, we need to countenance a symmetric relation of causal connection. In fact, causal theorists regularly do so. This will be looked at a little more carefully in the next section. But, quite apart from this, the case for regarding tachyon interactions as causal looks very strong. Tachyons have mass; they have energy and, in their interactions with bradyons (subluminal particles), they exchange energy. A tachyon interaction may change the momentum of a bradyon either by accelerating it or by being absorbed by it. This is, surely, unequivocally causal.

Lastly, let us look at the following rather conceptual (if you prefer, rather kinematical) objections to the tachyon idea. Consider the following criteria for particle-hood.

(1) For any non-accelerated particle, there is a frame of reference in which the events in its history occur in the same place and are separated only in time.

(2) For every frame, the places of events in the particle's history differ only if the times of the events differ.

(3) The temporal order of events in the particle's history is invariant for all frames.

(4) The number of particles and their identity is invariant for all frames.

These conditions, it might be argued, are necessary for us to regard a material line in spacetime as a continuant; that is, as giving us at each point on the world-line the same particle as at each other. Use of the Lorentz transformations on linear and curved tachyons paths show that tachyons breach all four criteria.[1] Thus, although there may be a material space-like line in spacetime for which a constant (its mass) is defined at each point, this cannot be regarded as a particle.

Let us put aside the question how compelling this argument is. (It is, I think, by no means overwhelming). It is like in strategy to a number of attempts to show that SR entails that there are no tachyons. However, what these arguments do is to attempt to deduce the Limit Principle somehow, not to use it as a basic postulate. What they attempt to deduce the Limit Principle from is the Invariance Principle, clearly enough. Now, even if some such argument succeeded, it would fail to show what the standard view really requires viz. that the Limit Principle is basic. What arguments like this would show, if any of them succeeded, is that it is the Invariance Principle which is relatively basic. The Limit Principle is basic, surely, only if one can appeal to it, quite directly, to rule tachyons out. Surely the tachyon literature shows conclusively that it has no such status, even if it is a consequence of SR and even if it is true.

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[1] But photons also breach the first.

It is not my plan to give more than this rather casual glance at the tachyon literature. More extensive discussions are cited in the bibliography.

4. CAUSALITY

Some obscurity surrounds which relation is intended by references in the literature to causality and which features make it proper to describe a relation as causal. More modestly, the literature leaves me uncertain how to answer some pertinent questions about cause; thus it leaves me unsure just how the causal theory can fairly be criticised in some of its aspects. How is the idea of causality, when it is proposed as a basis for SR, related to the idea examined by Hume and found so deeply problematic in philosophy ever since? When are we to understand causality itself as being *explicated* or *analysed* in the literature rather than merely indicated or identified and how may accounts of it run the risk of making circular the attempt to reduce temporal relations to causal ones? In what way is causality proposed as primitive? In what way does it define, explicate or give the physical basis for temporal relations?

One problem which seems clearly urgent for the causal theorist is to fix *non-local* relations, to connect events here and now with events there and then, without calling on temporal relations to do so. So what seems to be needed in the idea of cause is only the part of it concerning causal propagation, to be understood somehow independently of temporal ideas. To focus just on causal propagation has two advantages. First, it lets us avoid the thorny question how to distinguish cause and effect, a question which arises for local as well as non-local causal relations. So causal connection is the key idea, and it looks agreeably free of Humean complexities. Second, this relation can be understood as a symmetrical one, raising no questions about the direction of time or cause. This seems appropriate to the time-symmetric structure of SR basic laws and to its (widely agreed upon) lack of comment on temporal direction. It is unsuitable to look for a basis for SR in an asymmetric relation of cause.[1]

There are deeper reasons why we should allow a fundamental relation of causality which is symmetric. We want to leave room for theories of the direction of time (and cause) which base it on contingent facts - not just logically contingent ones, but facts that are contingent in the light of fundamental physical laws. A theory of this kind is the Boltzmann-Reichenbach-Grünbaum theory, in which the direction of time depends on the feature that the entropy of almost all thermodynamic branch systems runs from greater to less in the same temporal sense. This is thought to lie in something like a boundary condition, which may apply only in some (large) region of spacetime and which is no matter of physical law. It allows that, in other regions of spacetime, the condition may fail either because the vast majority of branch systems have their entropy running from greater to less in the opposite temporal sense to that in our own region, or because the branch systems do not, on the whole, increase their entropy in a common temporal sense. Such epochs may coincide with periods of expansion, contraction or stability in the size of a spatially finite universe, for instance. In any of these epochs mechanical interactions would comply with those same laws of continuity, contiguity, motion and energy exchange which make up the core of the idea of cause. So it seems right to speak of a basic idea of causal connection which is symmetric, not just in the weak sense that it is given by a disjunction (a causes b or b causes a) of sentences using a deeper asymmetric causal relation, but in the strong sense that it captures what is given in the time-symmetric laws fundamental to physics. It is in this symmetric sense that tachyon connections are to be understood as causal. That there is this symmetric idea of cause and that it is basic is, I think, perfectly acceptable to causal theorists and, indeed, defended by them.

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[1] See Mehlberg (1935) and Grünbaum (1973) for critiques of Reichenbach's (1958) use of the asymmetric mark method (also discussed in (c) below).

This feature of symmetry at least partly explains, I think, why explications or analyses appear to be offered for causality, though it is proposed as primitive. The relevant aspect of it has to be distinguished from cause more generally. More importantly for its aim in giving a basis for temporal relations, we need to see how to specify the causal relation, *at least in extension*, without recourse to temporal (or to spacetime) relations.

There are at least three ways in which a property might figure as a primitive basis for a theory. It might be a *conceptual* primitive, an idea so clear, well entrenched and unproblematic that no account of it will make it more readily understood. Next, though it might be imperfectly understood, it might nevertheless be so basic to the structure of the theory in question that no formulation of it could both give us the theorems which identify the theory yet fail to give the relation, and key assertions using it, a very prominent place. Thus one could not understand the theory's other main ideas without understanding the first one at least equally well. We might call such a property a *theoretical* primitive.

Lastly, it might be an *ontological* primitive; that is, a property so basic in the structure of the world (but not, necessarily, of the theory) that, despite our, perhaps dim, insight into it, there can be no more certain way of showing where the theory touches reality, so to speak, than to tie its ideas to this ontological primitive. It is clear, I think, that the standard view is committed to causality as a theoretical primitive of SR. It is not always clear to me how far the other (independent but compatible) notions of primitiveness are at issue in the literature. Whether one sees temporal relations as analysed or theoretically explicated by causal relations or the latter as providing the physical basis for the former may depend on the kind of primitiveness causality is reckoned to have.

Let us now look at several of these accounts of causality.

(a) In Reichenbach's (1958) and (1971) Grünbaum's (1973) and (1968) and van Fraassen's (1970) causal theories of time in SR, the notion of *genidentity* plays a very prominent role. This is not the same idea as causal connection, but is proposed as one kind of it. In Grünbaum's constructions, at least, it seems to play a more prominent role than causal connection itself. One can indicate what genidentity is in the following way:[1]

> e_1 is genidentical with e_2 iff (i) $e_1 = e_2$ or (ii) $e_1 \neq e_2$ and e_1 and e_2 happen to (are events in the history of) one and the same material thing.[2]

We can go on to indicate the intended extension of the relation of causal connection, as van Fraassen does (1970) p. 179, by saying that two events are causally connected if they are genidentical or connected by a light ray.

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[1] That this takes the form of a definition is not intended to insinuate that the idea is not primitive in any of the senses just described. The first disjunctive clause in the definiens could be dropped without real loss.

[2] Cf. Grünbaum (1973) p. 189 (1968) p. 57, van Fraassen (1970) p. 34.

Why does genidentity figure so prominently in these theories? It is not perfectly obvious that genidentical connections really are causal ones. How clear is it that the existence of something a while ago is the cause of its existence now? But I doubt that this query matters much. It seems to me that the appeal of this idea is that it enables us to speak of non-local connections without speaking of propagation as such; that is, without reliance on spatiotemporal criteria. Genidentity also seems to be used to display features, such as continuity, which causal connections (chains) generally show. In support of this interpretation of the role of genidentity, one finds van Fraassen saying that the "single basic strategy" of Reichenbach and Grünbaum "consists in *first* explicating the time order of the events on a single world line and *then* explicating the time order of all events by correlating the world lines (through the relation of causal connectibility)". (*Op.cit.* p. 182; italics in original. His own procedure is to reverse the order of this strategy.) In fact, as he says on this same page, the latter task is more easily understood as carried out by using the relation of topological simultaneity (causal non-connectibility). Thus non-local connections are set up by identifying world lines but not using the concepts of time or timelikeness to do so. The Limit Principle then says that all world lines lie within the light cone.

Genidentity has pleasing features as a primitive. It connects neatly with the very familiar idea of a continuant thing. It is clearly symmetrical. It makes no appeal to a prior concept of propagation or of time. It looks well qualified for conceptual primitiveness.

However, there are decisive objections to genidentity as a primitive, in the present context of use, at least. First tachyons count as material things. So unless SR says that there can be no tachyons it does not say that genidentity (hence causality) is confined to the light cone. So genidentity is not theoretically primitive and SR makes no fundamental assertion about it which would allow us to use it to identify the light cone.

But there are more damaging objections than this. Genidentity must identify exclusively timelike relations if it is to enable us to pick out world lines. It does not. Distinct events which happen to a voluminous material object, such as the earth, may well be simultaneous, hence spacelike connected. Of course, the earth is really an aggregate of more fundamental material things and genidentity may be intended here to apply only to these. But still, unless the idea of a fundamental material thing entails that every such thing is a strict point particle, genidentity cannot distinguish timelike connections from spacelike ones. For distinct events which happen to it could be simultaneous (in some frame) and occur in different places (for every frame). Now, first, it does not seem to be true that fundamental material things are actually
Quants strict point particles nor that any coherent notion of genidentity or causality can be ascribed to them. (See Reichenbach (1971) § 26, and Smart (1969) p. 391)). So genidentity does not appear to be an ontological primitive. Quite apart from these quantum problems, it is certainly not the case that SR anywhere claims or presupposes that some kind of atomic, let alone point-particle, hypothesis is true. It can be, and standardly is, expounded in terms of macro, spatially extended things (rods and clocks) and light treated as an expanding spherical wave front. It is, principally, a physics of fields and it would fundamentally misrepresent the theory to tie it, conceptually, to a strictly particulate hypothesis about the structure of matter. Thus, on this ground too, genidentity in the sense required does not seem to be a theoretical primitive of SR. A last weakness in this understanding of genidentity is that it makes a silent appeal to a spatial concept. Unless fundamental

things are conceived as spatial points, as continuants with only temporal extension, genidentity cannot identify the timelike relations it is required to pick out. Thus, for the Leibnizian programme of basing spacetime (spatial as well as temporal) relations on causality, it is not a conceptual primitive. Both Grünbaum (1968) and van Fraassen (1970) gave up the programme for spatial relations though Winnie's (1977) constructions must surely revive the hope of carrying it out. But genidentity cannot be used without circularity. Thus this first version of causality is in deep trouble quite apart from the problems of the tachyon hypothesis.

Grünbaum ((1973) p. 189) says that genidentity is, intuitively, "the kind of sameness that arises from the persistence of an object for a period of time". (See also his (1968) p. 57.) This understanding of genidentity might be used to free it from any appeal to the idea of a point particle concealed in the version just discussed (though I doubt whether this was Grünbaum's reason for giving the quoted comment). But this does clearly lean, quite fatally for conceptually reductive purposes, on the unanalysed idea of persistence in time. That cannot be a definition in the course of a Leibnizian reduction of the concept of time.

(b) By far the most common, brief statement of what causality is, says that events are causally connectible if a signal could be sent from one of them to the other. The Limit Principle then says that light is a first (fastest) signal. It is doubtful whether anyone thinks that this adequately explains the sort of primitiveness causality has if it is to play the role for SR envisaged in the standard view. But let us see, first, what advantages this account might seem to offer.

One of the features of tachyons, as we saw, is that they cannot be used to pass information or to signal (on the natural assumption that the "laws" of thermodynamics are Lorentz invariant). This "first signal" version of the Limit Principle would seem to exclude tachyon connected events as causal since the signalling relation would coincide with theforward light cone. This suggests, at first glance anyhow, the idea that, since *information* (needed for setting clocks, for instance) cannot be sent from here to there any faster than light, we can never know how to synchronise clocks here with clocks there. Thus the relativity of simultaneity would rest on an *epistemological* fact.

The weakness of suggestions like this is, as before, that they really do not seem to be basic to SR in the way wanted. The idea of a signal is really the idea of a kind of irreversible process which transmits information or a mark. Thus it is an idea which belongs to thermodynamics and not at all, fundamentally, to SR. All the basic laws of SR are time-symmetric, unlike those of thermodynamics, and are incapable of specifying irreversible processes and, therefore, of capturing the idea of a signal. This puts the matter rather simplistically but the point seems very widely accepted. I include it here for the sake of completeness rather than as controversy.

Too Comp.

(c) In other places, genidentity is treated as if it were not a primitive relation on which causal connectibility is based. Instead, both these relations are defined in terms of others. Reichenbach ((1971) pp. 224-7) appears to *define* material genidentity[1] as a prelude to his arguing that the relation does not apply to particles in quantum mechanics. He bases material genidentity on three criteria: that change is continuous; that any one particle is spatially excluded by any other; that the interchange of spatial position is verifiable (by marking objects). In reply to an earlier suggestion of mine that causality might not be fundamental to SR, Salmon (1981) p.   ) refers to various discussions (1975 b, 1977) he has given as to the nature of causal processes and what distinguishes them from pseudo processes. One finds there that criteria are offered for causality which are analogous to

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[1] This, rather than functional genidentity, is what concerns us at present.

(improvements on) Reichenbach's. Briefly, Salmon proposes both spatio-temporal continuity and the ability to carry a mark as criteria for causal processes. It is the latter which distinguishes causal processes from pseudo ones. As I understand him, Salmon wants to develop this latter idea in such a way that we can understand causal processes in a time-symmetric way, and thus he avoids the problems just discussed in (b) above. This makes for a very interesting development of the idea of cause.

Before pursuing it in more detail, however, I will point out, briefly, two difficulties which any account along these lines must run into if it wishes to show how causality in SR allows us to realise Leibniz's programme. First, Reichenbach and Salmon make it a necessary condition for a process to be causal that it be spatio-temporally continuous. But this idea already requires at least that we can understand and identify what it is for two events to occur at different times or at different places from each other. A concept of causality for which spatiotemporal continuity is a necessary condition would thus be disbarred as circular from serving Leibniz's aim to reduce spatial and temporal relations to causal ones, whether this is intended to identify the relation intensionally or extensionally. Second, material genidentity and causal process break down for quantum phenomena as both Reichenbach (loc. cit.) and Salmon ((1977) pp. 132-3 § 54 passim) make quite clear. But, if that is so, causality does not really seem to be a fundamental relation in the world at all and so no fit candidate as the ontological primitive basic to SR. Further, to view causality as basic to SR is to view the theory as inconsistent with quantum mechanics in a basic way. No doubt the problems of quantised gravitation in General Relativity must be recognised. But there does not seem to be real conflict between SR and quantum theory. It seems an unfortunate ambition to create one by insisting that SR be based on causality.

Salmon's main idea, however, is the ability to transmit a mark and we must look at this with some care. It seems best and fairest to let Salmon speak for himself as to what his intentions are, especially as he does so with admirable clarity.

> In the context of relativity theory, it is essential to distinguish causal processes, such as the propagation of a light ray, from various pseudo-processes, such as the motion of a spot of light cast upon a wall by a rotating beacon. The light ray itself can be marked by the use of a filter, or it can be modulated to transmit a message. The same is not true of the spot of light. If it is made red at one place because the light beam creating it passes through a red filter, that red mark is not passed on to the successive positions of the spot. The motion of the spot is a well-defined process of some sort, but it is not a causal process. The causal processes involved are the passages of light rays from the beacon to the wall, and these can be marked to transmit a message. But the direction of message transmission is from the beacon to the wall, not across the wall. This fact has great moment for special relativity, for the light beam can travel no faster than the universal constant _c_, while the spot can move across the wall at arbitrarily high velocities. Causal processes can be used to synchronize clocks; pseudo-processes cannot. The arbitrarily high velocities of pseudo-processes cannot be exploited to undermine the relativity of simultaneity.

Consider a car travelling along a road on a sunny day. The car moves along in a straight line at 60 m.p.h., and its shadow moves along the verge at the same speed. If the shadow encounters another car parked on the verge, it will be distorted, but will continue on unaffected thereafter. If the car collides with another car and continues on, it will bear the marks of the collision. If the car passes a building tall enough to cut off the sunlight the shadow will be destroyed, but it will exist again immediately when the car passes out of the shadow of the building. If the car is totally destroyed, say by an atomic explosion, it will not automatically pop back into existence after the blast and continue on its journey as if nothing had happened. (1975, p. 129-30)

The question can still be reformulated. What do we mean when we speak of transmission - how does the process *make* the mark appear elsewhere within it? There is, I believe, an astonishingly simple answer. The transmission of a mark from point *A* in a causal process to point *B* in the same process *is* the fact that it appears at each point between *A* and *B* without further interactions.... (The same result could be accomplished, of course, by outfitting the spotlight itself with a red lens, but that would not count as *marking* the spot on the wall, for it would not constitute a *local* interaction with the spot which moves around the wall....) The basic thesis about mark transmission can be stated as follows: *A mark that has been introduced into a process by means of a single intervention at point A is transmitted to point B if it occurs at B and at all stages of the process between A and B without additional interventions*. (Italics in original (1977) p. 221.)

Now, the reason that the mark method, by itself, is inadequate to establish an unambiguous temporal direction is, essentially, that we have to understand the distinction between imposing a mark and removing a mark - for example the difference between making a chalk mark on a billiard ball and erasing such a mark. But this difficulty

> does not mean that we cannot use the mark method for establishing causal connections, or tracing out causal processes, provided we remain non-commital regarding their temporal directions. Suppose, for example, that there is a beam of light shining on a wall, and we notice that the colour of the spot on the wall changes from white to red and red to white from time to time. Suppose that we also notice a red filter which is moving in and out of the beam. Suppose, moreover, that the presence or absence of the filter in the beam is highly correlated with the colour of the spot on the wall. We have said nothing, as yet, about the filter causing the beam to be red; so far, it is equally open to say that the presence of the red filter is caused by the colour of the spot on the wall. Nevertheless, we can say, without committing ourselves to a temporal direction, that there is a causal process present here. ((1975b) p. 171.)

This is an important clarification of the concept of causality. The last passage makes clear that Salmon is not relying on a prior understanding of irreversible process, of imposing as against erasing a mark. Thus he is proposing something quite distinct from the idea that causality is the asymmetric relation of sending a signal. It is the capacity to retain (and hence transmit) a mark which Salmon is emphasizing.

I do not want to try to debate the main point that Salmon was making in these papers: that is, a basic ingredient in the style of scientific explanation which is familiar to us is the idea of a causal process and the existence of such processes is a contingent fact (if a fact at all) about the world. Whether that point is sound or not is irrelevant to what I am arguing.

Salmon does not consider at length any possible objections to the idea that causality in this sense is co-extensive with the light cone. However, he certainly claims that it is, in several places ((1975b) p. 141; (1977) p. 217). He says very briefly in a footnote (1977) p. 217 why he ignores tachyons:

> I am ignoring speculations about "tachyons" - particles with velocities greater than light - because (1) if there were such things and *if they could be used to transmit signals* the logical structure of special relativity would be seriously affected, and (2) all efforts to discover tachyons have failed, so there is no reason to believe such things exist. (His italics.)

The second of these reasons is irrelevant to the question whether or not it is a basic thesis of SR that causality defines the light cone by being co-extensive with it. Of course, Salmon does not claim that it *is* relevant. The first reason is somewhat more complex. I take it that the logical structure of SR would be seriously affected by the tachyon paradoxes discussed in his ((1975) pp. 122-3). This claim seems adequately answered by the brief discussion in § 3 of the present paper and in the tachyon literature more widely. The natural assumption about the laws governing irreversible processes, including signals and marks, is that they will be Lorentz invariant. So tachyons could not be used to transmit signals. Should the natural assumption be false then, on the one hand, the sense in which tachyon signals were irreversible processes would be rather attenuated and, on the other, the non-lawlike sort of simultaneity which tachyon signals offered would not oblige us to accept it in preference to the relative simultaneities of Lorentz frames to which all truly lawlike phenomena would still conform. In neither case, does it seem that the logical structure of SR would be seriously affected, after all.

But these remarks do not directly address the most interesting aspect of the suggestion which Salmon proposed. The suggestion does not really depend on ideas like signalling, or engraving as distinct from erasing a mark, and so on. Quite clearly the core idea is that the mark will occur at all points in the causal process between A and B. It does not matter, for the purposes of the criterion, whether it is being transmitted from A to B or from B to A. The question we have to scan is whether SR tells us that this criterion can somehow be used to identify the light cone.

If I have understood Salmon correctly, then it should make no difference to the criterion whether the feature which occurs at all points between A and B without further local intervention is a reversible or an irreversible feature - spin in the one case or a scratch in the other, for example. I will make that assumption. I assume, too, that we can discuss the proposal adequately in terms of classical concepts and ones which apply to macro material things. On the one hand the quantum complication can hardly aid Salmon's causal argument and on the other it is not clear how to mark either a quantised or strict point particle. So let us look on the tachyon as a little markable billiard ball.

The following ideas then make perfectly good sense within SR. A tachyon is involved in a local interaction at a spacetime point A and a local interaction at a distinct point B. There is no other local interaction between the points. At all points between A and B the particle is spinning. With respect to some frame F, the interaction at A causes the particle to spin until this is braked by the interaction at B. With respect to some other frame G, the B interaction is the cause of the spin, which is braked at A. (The basic idea of spin as a reversible process with "reversible cause" comes from Reichenbach (1971) pp. 184-6, of course).

I claim, as before, that SR asserts nothing inconsistent with the capacity of tachyons to transmit such a mark, consequently it says nothing which would allow one to exploit this capacity to carry a mark as a criterion which could use to identify the light cone.

(d) It seems appropriate, next, to look at the pioneering and, by now, influential work of Robb (1914). While Robb's influence has been suitably acknowledged there seems to be little discussion of the materials which he actually worked with.

? Omit

Robb's primitive relation is *after*. He defines 'before' by means of it, so that it will do the same work as the *elsewhen* relation which I used at the end of §2. He postulates that *after* is asymmetric; that there is at least one element after any element and so on. However, in the Introduction to his book Robb offers some remarks about this primitive as if he felt obliged at least to tell us which relation it is. Consequently, there is some uncertainty as to whether *after* really is the primitive of Robb's system or whether the ideas used in his Introductory remarks should not be preferred. This uncertainty appears to be the only basis for taking Robb as a *causal* theorist.

A glance at the ideas Robb makes use of in his Introduction and which he sees as shedding some light on the idea of *after* strongly suggest philosophical motivation. A key remark is the following (p. 4; his italics):

> Of any two elements of time of which I am *directly* conscious one is *after* the other.

(I guess that Robb also meant to imply that one is aware of the one event *as* after the other). He goes on to claim that the set of instants of which any one subject is directly aware form a series in linear order (the ordering relation being, I guess, S is aware of x as after y). Evidently, Robb wants to tie the after relation to what he sees as a solid epistemic anchor. He later extends the relation by using the following condition:

> If an instant B be distinct from an instant A, then B will be said to be after A, if, and only if, it be abstractly possible for a person, at the instant A, to produce an effect at the instant B. (p. 7)

Robb seems here to want to side with the prevailing philosophical psychologism of the period, but, of course, the anthropocentric aspects of these glosses on after cannot be taken really seriously since human powers to discriminate and act are too crude to do the work required of after. Perhaps, also, he wished to defer to the idea that temporal relations have to be based on some other relation as a requirement of philosophical hygiene. But it is all too clear why this rather vague part of the discussion is relegated to an Introduction. Robb does not really provide a suitable basis to make plausible the claim that SR may be based on causality.

(e) Next, could we not simply include it as a postulate of SR that causality is co-extensive with the light cone, since it looks highly unlikely that there are any particles such as tachyons? (This is a suggestion put to me in discussion, if I understood him, by Bas van Fraassen.) This would give us two versions of SR, a classical one in terms of which the existing tachyon literature is consistent and a novel one which rules tachyons out simply and directly by a postulate.

That could be done, of course. But it would not hold much philosophical interest to do it. Surely what has been under close discussion in the philosophical import of SR is whether or not causality (through the

Limit Principle) is the necessary foundation of the relativity of simultaneity and, more generally, of the Lorentz Invariance of the laws of physics. I have been arguing that it is not. The Limit Principle is not the basis of the Invariance Principle, which stands entirely without its support. To include the Limit Principle as a subsequent postulate may have several interesting consequences, but not the consequence that it thereby becomes necessary to the more powerful parts of the conceptual structure of SR. Its inclusion would do nothing to show us how the concepts of space and time in SR depend on the idea of causality, which it was Leibniz's programme to show.

(f) Light connections are included among causal connections in all accounts of what causality is. It is quite certain that one can define the light cone in a completely satisfactory way by means of light connection. If e_1 is in or on the light cone at e_2 then e_2 is in or on the light cone at e_1. Both relations in thedisjunction are symmetrical. If e_1 is on the light cone at e_2 then the light cones at e_1 and e_2 intersect in a null geodesic, a path for a light ray connecting them. If e_1 is in the light cone of e_2 then the cone at e_1 intersects the cone at e_2 in a spherical spacelike surface. For any point P on this surface there is a null geodesic linking it to e_1 and another linking it to e_2. These identify the path of a light ray linking e_1 and e_2 by an appropriate reflection at the point P on the spherical surface. It is certainly a very elementary and basic postulate or theorem of SR that light is not propagated outside the light cone. As just indicated, it is easy to show that every timelike connected pair of events can be connected by a reflected light ray. There can be no question at all that the relation of light connection is a conceptual and a theoretical primitive of SR. It also looks to be an ontological primitive.

Does this mean that causal theorists have overlooked a simple and eminently satisfactory version of their theory? Well, if we identify the light cone and its interior by means of light connections, it is not clear how this shows *causality* to be basic in SR. It is true that a light ray is a form of causal propagation, but SR does not seem to single out the causal aspect of light as the important feature of it. If SR entailed the Limit Principle as a basic postulate then it would be plausible to regard the fundamental role it gives to light as that of forming the limit of causality. The theory would tie light deeply into the structure of causality. But SR does not do so. It is something else specific to light which SR singles out for special notice.

It is easy to say what this feature is in the concepts of the relativity interpretation. Light is always *propagated*; it is never *at rest* in any frame, even if one admitted frames corresponding to all coordinate systems allowed by the Principle of General Covariance. That is a primary ontological fact about light. In the spacetime interpretation, it corresponds to the fact that the light cone consists in null geodesics. This requires that, in any coordinate system, both the spatial and temporal coordinate differences are non-zero for any two distinct events connected by a (non-reflected) light ray. That light divides the positive from the negative intervals of spacetime is the main theoretical feature of it in SR. It is the meet of the elsewhere with the elsewhen and this is its deep topological significance. This is the basic, structural or ontological fact about light which SR makes so prominent and this is implied in any programme to place light as the fundamental relation of SR. The concept of light is the concept of that which is propagated. It is deeply spatiotemporal. Space and time are absorbed in spacetime by a prior absorption of each into the spacelike and the timelike (the elsewhere and the elsewhen). Lightlike connections form a common boundary to these, in the sense that distinct lightlike connected events are always elsewhere and elsewhen from one another. These are the deepest seated conceptual facts about the relations of the spatial and the temporal to spacetime. They place light in the conceptual position of that which travels. So the conceptual role of light in the theory cannot be divorced from these spatio temporal ideas. It divides the timelike from the spacelike. That is why light cannot be used to reduce temporal relations to causal ones.

5. FOUNDATIONS FOR SPACETIME STRUCTURE

The main drift of argument so far has been in this direction: the crucial task in constructing foundations for SR is to find a means of identifying the surface of the light cone and its interior. For largely philosophical reasons, causal relations have been mistakenly preferred to temporal ones as a primitive basis for this identification. The mistakes have been that SR does not postulate nor even entail the Limit Principle which is a necessary condition for causality to identify the light cone and its interior and also that, even if the Limit Principle were true, causality turns out, on examination, not to be more primitive in SR than spatial or temporal ideas are.

I want to go on to argue, now, that one need not base the structure of spacetime, at least, on some means of identifying the light cone and its interior. One could equally well base it on some means of identifying the surface of the cone and its exterior. This would be an unusual procedure, but none the worse for that. If one can base it, equally strongly and elegantly, on space-like rather than time-like relations then spacetime certainly does not specify causality as its uniquely primitive basic relation, whether or not the Limit Principle is a postulate in some formulation of SR.

There is no doubt that standard physics expositions of SR, with no philosophic axe to grind, strongly suggest some sort of priority for the time-like line in spacetime, the world line, or at least to time-like relations and connections. How the theory suggests this and whether the suggestion springs from something fundamental in it are questions we must now pursue.

At least two features have made the idea of a world-line (that is, a material, timelike extended line in spacetime) of more interest than the counterpart idea of a material spacelike extended line. Neither feature is built very deeply into SR. First, the range of familiar objects and their more fundamental spatially smaller parts readily suggests the idea of a decreasing series of spatially smaller objects with a strict point mass at its limit. This, together with the fact that familiar objects frequently endure for rather long periods, prompts the idea of an eternal point particle and of the principle of the conservation of matter. This is recognisably an approximative idea and not at all a fundamental one. Spacetime theories are much more profoundly concerned with field concepts than with proposals about the constitution of matter. The second feature is that clocks (of whatever kind) provide operationally for a measure of proper time, the measure of interval along timelike curves. That, too, is approximative. Real clocks may be affected by acceleration. Only ideal clocks are unaffected by the possibly intensive curvatures on a timelike curve. Finally, it is not clear that the idea of a clock is fundamental in SR.

Nothing analogous to these features can be found for spacelike connections. First, spacelike material lines (surfaces, volumes) lie at the limit of an increasing series of spatially larger objects and a decreasing series of temporally briefer and briefer material things.

That seems to be the construction analogous to that of the world line, at least. Nothing familiar in our experience motivates the pursuit of either series towards its limit. (The tachyon hypothesis is motivated in a quite different way, but that need not concern us now.) Secondly, though rods (ideal rods) deliver a constant rest length[1] this does not give us the direct measure of a spacetime interval. Rest length is a spatial measure: it tells us a distance between two parallel time-like lines (the world lines of the end points of the rod). But this spatial measure is not taken along any spacetime line or curve. The idea of a spatial interval (which light can travel across, for example) is best understood as tied rather to the relativity interpretation than to the spacetime interpretation. It is not an interval which connects events. Light can intelligibly be said to travel across spatial but not across spacelike intervals since these are defined as lying outside the light cone.

But these features need more careful scrutiny. We can usefully split the problem into two others. Does spacetime structure reveal a more basic or more primitive role for time or the timelike as a matter of its formal geometry? Does it do so operationally.

We can give a rather unqualified "No" as answer to the first question. Let us look at this in the perhaps rather specialised, but also rather revealing, context of a coordinate-free metric treatment of spacetime. It will be enough to consider just the problem of defining the general spacetime interval between two point events (where the interval is not Δs but Δs^2). Standardly, the interval between any pair of spacetime points p and q is a construction using proper time and the light cone. Choose a time-like curve through p and take the points r and s in which this curve intersects the light cone through q. Let t_1 be the proper time from p to s and t_2 the proper time from r to p. (Whether the proper time is positive or negative depends on the direction in which one takes it. If time itself has a direction, this will not be arbitrary). The space-time interval is then, quite simply, the product of these proper times. (This assumes a (-+++) signature of the metric.) It will be positive for spacelike intervals, negative for timelike intervals, as in the figures below.

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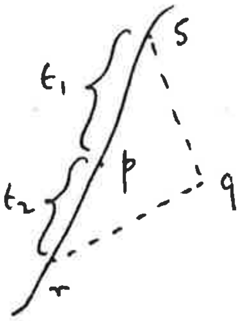
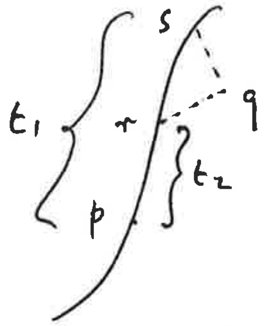
[1] Strictly, not even ideal rods are rigid under rotation, for example.

t_1, t_2 each positive
(spacelike interval)

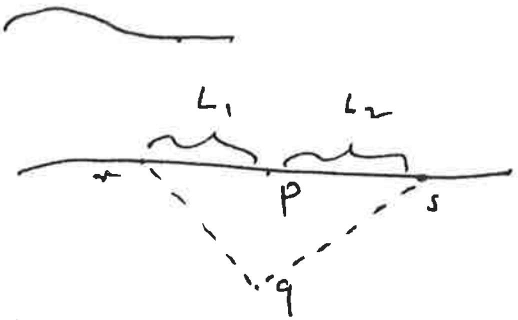


t_1 positive, t_2 negative
(timelike interval)

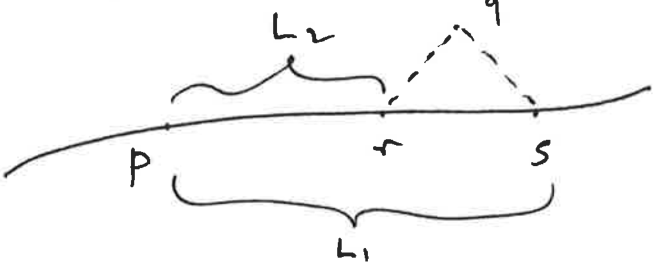


Constructions like these are explained in some detail, but very simply in Geroch (1978) Ch. 5 esp. pp. 80-96).

Formally, it is easy to find the dual of any such construction, using the proper length of spacelike lines and the light cone. In the figures below, r and s are points in which some spacelike curve through p intersects the light cone at q.



Timelike interval: L_1 and L_2 have the same sign



Spacelike interval: L_1 and L_2 differ in sign

Let L_1 be the proper length from p to s along the curve and L_2 the proper length from r to p. Again, the sign of the length depends on its direction. Unless space itself has a direction, this will be arbitrary. The expression for the interval is, analogously, simply the product $-(L_1 L_2)$ (for the same metric signature). Geroch also gives expressions for the spatial and temporal coordinate intervals, where the time-like line approximates the axis of a Lorentz coordinate system. The duals of these for the case where the timelike line approximates a spatial axis of a Lorentz system are given below and compared with their originals.

$x = \frac{1}{2} (L_1 - L_2)$ Geroch: $x = \frac{1}{2}c (t_1 + t_2)$

$t = \frac{1}{2} (L_1 + L_2)/c$ $t = \frac{1}{2} (t_1 - t_2)$.

The illustration shows that spacelike duals of timelike based constructions are a general formal feature of spacetime geometry. So this geometry gives no superior formal status to timelike as against spacelike connections, nor to causal relations, even if the Limit Principle is entailed by SR or a postulate of it in some axiom system for the theory.

When we turn to reflect on operations in measurement and experiment we find what seems to be a clear preference for the timelike. We can regard an observer as on (approximating to) a world line and as sending a signal from it to q and observing the signal reflected back from q. This replaces the rather abstract account of the procedure given before. The observer now takes the relevant readings of proper time directly from his clock. But no observer can be on the spacelike curve through p, in the analogous sense. In the first of the two figures illustrating the spacelike construction, one can see how light signals can be sent from q to r and s, since the spacelike line lies in the direction of the forward light cone at q. But if the line lies in the backward light cone at q, as in the second figure, it is not so clear what the procedures of signalling would be.

I doubt that we can attach much weight to any of these operational disanalogies save one. That is the lack of any spacelike counterpart to a clock which would allow us to measure the interval along a spacelike curve. This needs more careful pondering.

Rods deliver a constant rest length. From a spacetime viewpoint this is something like the constant distance between two parallel timelike lines (the world lines of the end points of the rod). But it is not any kind of measure of a spacetime interval. Given a point on one of these parallels, infinitely many spacelike lines through it intersect the other parallel. These spacelike lines differ in proper length yet only one rest length seems to correspond to all of them. Thus the rest length seems not to give the measure of any spacetime interval. (See Nerlich (1981) p. for a fuller account).

Nevertheless, there is (and must be) a well defined connection between rest length and proper length, both conceptually and operationally. Take two spacetime points p and q with spacelike separation. These are not the end points of a rod, of course, but they can mark events which might occur at the end points of a rod. Geometrically one takes the class of all pairs of parallel timelike lines, the first member of which contains p and the second q. Each pair represents the trajectories of the end points of a rod at rest in some Lorentz frame. Any such rod has a rest length as a constant of it. Now consider the rest lengths defined by this class of pairs of parallels. It contains a unique maximum L, together with all positive real values less than L and greater than zero. So the class defines only this maximum, L. *Now, this rest length L is also the proper length measure of the spacelike interval pq*. Every proper length may be defined by a rest length in this way.

This picture of the connection between rest-length and proper length has some further interesting consequences. If we ask which pair of parallel lines establishes this necessary connection between rest length and proper length, we find the answer that it is the pair *orthogonal* to the spacelike line joining p and q. That is, each parallel line is also parallel to the timelike axis of every Lorentz coordinate system for which p and q have the same time coordinate, and so they lie on the spacelike axis of some such frame. In the relativity interpretation, the construction which establishes the necessary connection between the ideas of the proper length between two spacetime points and the rest length of rods also identifies the Lorentz frame for which two such spacetime points are simultaneous and the related rod is at rest. Thus there clearly is an essentially metrical construction which picks out a class of simultaneous events which corresponds, in a non-arbitrary way, to a given class of rest points. That is, even if we use the philosopher's idea of a frame of reference criticised for its inadequacy in §2 pp. 11-12, we can still associate classes of simultaneous events with it in just one non-arbitrary way; this will give us, in fact, the complete Lorentz frame of reference as a result. No assumption or connection about the speed of light is made at any point. As in Malament's undoubtedly deeper, topological construction of orthogonality, one can construct just Lorentz simultaneity or Lorentz frames and no others. It is worth pointing out that in Winnie's treatment of SR without one-way velocity assumptions (with ϵ treated as a free variable), expressions for both rest length and proper length contain no ϵ variable; that is, they are convention free (See Winnie (1970)). So this sheds further light on the claim in §2 that neither simultaneity nor the Invariance Principle need be conceived of as having its factual import debilitated by conventions.

Returning now to the problem of operations of measurement of spacetime, one finds that there is, after all, an operation which gives us the proper length along a spacelike interval. If e_1 and e_2 occur at the ends of one's measuring rod and one sees them together (simultaneously at one place) at the mid point of the rod then the proper length measure of the spacelike interval $e_1 - e_2$ is the rest length measure of the rod.

It would be incautious to make a strong claim about the operational symmetry between the spacelike and timelike approaches to SR on the basis of this discussion. Nor is it necessary to do so. The operations we have been scrutinizing are essentially metrical ones, the question being whether the measuring of timelike trajectories is more accessible operationally than the measuring of spacelike paths. But the deep and elegant studies of spacetime geometry carried out by Robb, Zeeman, Malament, Winnie and others show that a separate metrical development of spacetime is not necessary. What these studies make clear is that we need only procedures which will decide, for any given event, which other events are in (or on the surface of) its light cone. No metrical question need be settled. The whole metric congruence structure can be built on that very modest topological basis.

It should be easy to see, at this stage, that such timelike constructions as these have spacelike duals. So it must also be true that we need only procedures which will decide, for any given event,which other events lie on the surface of the light cone or outside it. Once again, no metrical question need arise. The whole metric congruence structure of spacetime can be built on that very modest topological basis. A construction of this kind uses the elsewhere relation rather than elsewhen. (Notice that, for distinct events e_1 and e_2, if e_1 is on the surface of the light cone at e_2 then e_1 is elsewhere from e_2.) So spacelike relations provide a basis for spacetime structure just as satisfactory as that given by timelike ones,[1] and so at least as satisfactory, but utterly different from, a basis which might be found in causality should the Limit Principle turn out to be a fundamental postulate of SR (despite all the evidence against this possibility).

6. CONCLUSION

The standard view is a thesis of philosophy. It is easy enough to lose sight of this fact in the necessarily detailed reflections on SR by which someone supports or opposes the view. At present, the strongest plank in the causal theorists' platform seems to be the deep and elegant constructions by Zeeman, Malament and Winnie which show how much of the structure of SR can be built on the topology of a single relation. One needs to remember that these constructions, revealing as they are, do not themselves show more than that some one relation will do the trick. They do not show that this one relation actually is causality rather than another relation and have, I think, no tendency whatever by themselves to settle the philosophical question as to whether it is *causality* that can or should be used to reduce temporal or spacetime relations to something else.

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[1] Perhaps it is obvious, but elsewhere is a spacelike, not a spatial, relation; elsewhen, analogously, is timelike, not temporal.

Another main philosophical issue on which causal theorists and others may divide is the issue of what counts as physical. I think that Grünbaum's remarks on the problem of tachyons are directed at a particular stand on this issue ((1973) pp. 824-7). He speaks of "the philosophical objections to this gambit of grafting the ontology of one theory of time order onto a physics of time order which is alien to it" (p. 824); and, later, "Why, I ask, are the relativistic time order relations still ontologically sacrosanct, if there is indeed superluminal causal connectibility among events?" (p. 827).

I take it that Grünbaum thinks that unless genidentical and causal connections are confined to the light cone then there cannot *be* anything - more explicitly, I think, there cannot be anything *physical* - to *constitute* real and therefore absolute temporal relations. But any such response depends on there being precise limits to what counts as physical and thus as the existence of physical features. It depends, I believe, on the view that time relations, not only may be, but must be *based on something else*. It depends on the view that time relations cannot themselves be physical, that spacetime itself is not an element in the ontology of physics and that features of spacetime cannot be physically basic.

This is not the place to examine the issue. (Grünbaum's writings may be seen as an extended commentary on it; my own, quite different, view is argued at length in Nerlich (1976)). But it is the same as the issue whether the Invariance Principle or only the Limit Principle can provide a properly *physical* basis for spacetime relations (quite apart from the question whether SR entails the latter). The Limit Principle sees the conical ordering of spacetime as constituted by the enclosure of matter and light within the light cone - it sees the cone as *constituted* by that limitation. That is undoubtedly physical. Indeed it is, very nearly, *material*. The Invariance Principle does something quite different. It speaks of light not as the limit of matter but as occupying a crucial structure *in spacetime*, a structure described, essentially *indirectly* by reference to a special class of coordinate systems for spacetime. Interpreted more directly, it characterises light as forming the boundary between positive and negative spacetime intervals, as the overlap of the elsewhere with the elsewhen. The philosophy which makes the Invariance Principle central to SR is a philosophy which takes spacetime and this feature of it as basically, irreducibly, physical but not (not *at all*) material. That is a main issue between distinct ontologies of the physical. Though it is correct, in some sense, to follow Minkowski in saying that, in spacetime, space and time shrink to mere shadows, it might be better to say that they are shown to be shadows of the spacelike (the elsewhere) and the timelike (the elsewhen) relations. Then SR can be seen as telling us, not something about the relations of matter to light, but about the interesting union of the spacelike, timelike and lightlike relations in spacetime. Metaphysically, we can bestunderstand its message, not as a materialist, but as a physicalist one about a physical particular - spacetime. This is significant not just for the metaphysics of SR but for the metaphysics of scientific theories generally. That is at least a large part of what this debate is about.

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BIBLIOGRAPHY

Berger, G. (1972) 'Temporally Symmetric Relations in Minkowski spacetime' *Synthese* *24*; pp. 58-73.

Bilaniuk, O.M.P. and Sudarshan, (1969) 'Particles Beyond the Light Barrier' *Physics Today* 22; pp. 43-51.

Earman, John (1972) 'Notes on the Causal Theory of Time' *Synthese* *24*; pp. 74-86.

Feinberg, G. (1967) 'Possibility of faster than light particles' *Physical Review* *159*; pp. 1089-1105.

Friedman, M. (1977) 'Simultaneity in Newtonian Mechanics and Special Relativity' in John Earman, Clark Glymour and John Stachel (eds.): *Foundations of Space-Time Theories*. Minnesota Studies in the Philosophy of Science. Vol. VIII.

Geroch, Robert (1978) *General Relativity from A to B*. University of Chicago Press.

Grunbaum, Adolf (1968) *Modern Science and Zeno's Paradoxes*. London, Allen & Unwin.

(1973) *Philosophical Problems of Space and Time*, 2nd ed. Dordrecht, Reidel.

Lacey, Hugh M. (1968) 'The Causal Theory of Time: A Critique of Grünbaum's version' *Philosophy of Science* *35*; pp. 332-354.

Malament, David (1977) 'Causal Theories of Time and the Conventionality of Simultaneity' *Nous* *11*; pp. 293-300.

Mehlberg, Henryk (1935) 'Essai sur la théorie causal du temps' *Studia Philosophica* *I* and *2* (1937).

(1966) 'Relativity and the Atom' in P.K. Feyerabend and G. Maxwell (eds.): *Mind, Matter and Method: Essays in Philosophy of Science in Honor of Herbert Feigl*. University of Minnesota Press.

Nerlich, Graham (1976) *The Shape of Space*. Cambridge University Press.

(1981) 'Simultaneity and Convention in Special Relativity' in R. McLaughlin (ed.) *What? Where? When? Why?*

Popper, K.R. (1956) 'The Arrow of Time' *Nature* *177*; p. 538.

(1957) 'Irreversible Processes in Physical Theory' *Nature* *179*; p. 1297.

Recami, E. & Mignani, R. (1974) 'Classical Theory of Tachyons' *Riv. Nuova Cimento* 4 (series 2); pp. 209-90.

Reichenbach, Hans (1958) *Philosophy of Space and Time*. Dover.

(1971) *The Direction of Time*. University of California Press.

Robb, Alfred A. (1914) *A Theory of Time and Space*. Cambridge University Press.

Salmon, Wesley C. (1975a) *Space Time and Motion*. Dickenson.

(1975b) 'Theoretical Explanation' in S. Körner (ed.) *Explanation*. Blackwell.

(1977) 'An "At - At" Theory of Causal Influence' *Philosophy of Science* *44*; pp. 215-44.

(1981) 'Replies to Critics' in R. McLaughlin (ed.) *What? Where? When? Why?* 1981.

Sklar, Lawrence (1977) 'Facts, Conventions and Assumptions in the Theory of Space-Time' in John Earman, Clark Glymour and John Stachel (eds.): *Foundations of Space-Time Theories*. Minnesota Studies in the Philosophy of Science. Vol. VIII.

Smart, J.J.C. (1969) 'Causal Theories of Time'. *Monist* 53; pp. 385-395.

van Fraassen, B.C. (1970) *An Introduction to the Philosophy of Time and Space*. Random House.

Weinberg, Steven (1972) *Gravitation and Cosmology: principles and applications of the general theory of relativity*. Wiley.

Winnie, John A. (1970) 'Special Relativity Without one Way Velocity Assumptions' Parts I and II. *Philosophy of Science* *37*.

(1977) 'The Causal Theory of Spacetime' in John Earman, Clark Glymour and John Stachel (eds.): *Foundations of Space-Time Theories*. Minnesota Studies in the Philosophy of Science. Vol. VIII.

Zeeman, E.C. (1964) 'Causality Implies the Lorentz Group' *Journal of Mathematical Physics* 5; pp. 490-493.

(1967) 'The Topology of Minkowski Space'. *Topology* *6*; pp. 161-70.